Membrane Biological Non-Oily Wastewater Treatment System for Ships

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ABSTRACT

Ships generate significant quantities of blackwater (human waste) and graywater (from showers, sinks, galleys, and other shipboard spaces). Increasingly restrictive wastewater discharge regulations in the U.S. and around the world are creating significant challenges for ship designers and operators. Because the ability of ships to hold wastewater is severely limited, there is growing interest in shipboard applications of wastewater treatment/concentration technologies. Research and development has recently focused on membrane-ultrafiltration technology as an affordable solution for meeting shipboard space, reliability, safety, vibration, and other unique marine requirements. Wastewater treatment based on aerobic biological pre-treatment, membrane-ultrafiltration, and ultraviolet light disinfection has shown great promise for meeting expected discharge limits and shipboard constraints. This system first aerates the raw wastewater in a bioreactor, which promotes the growth of existing bacteria that digest the dissolved organics. The aerated wastewater is then pumped from the bioreactor through ultrafiltration membranes, whose semi-permeable surfaces separate the bacteria and suspended solids from the water. The clarified effluent from the membranes is passed through an ultraviolet light disinfection system that avoids the use of chlorine or other chemicals. The configuration of the bioreactor/membrane system varies with the type of membranes used, especially whether they are internal or external to the holding/processing tank. These differences are reflected in the systems' relative performance, space, weight, maintainability, and cost characteristics.

INTRODUCTION

Large-complement ships generate significant quantities of blackwater and graywater, up to 350,000 gal/day. Blackwater is human waste generated by the ship's crew. Graywater drains from hotel and commissary-type activities aboard ship; common sources of graywater are showers, sinks, laundry, and galley and scullery equipment. United States law prohibits the discharge of raw sewage from ships within 3 nautical miles (nm) of shore. New international sewage discharge restrictions being considered may extend the no-discharge zone well beyond 3 nm. Furthermore, the use of chlorine treatment for disinfection of sewage is widely discouraged or prohibited. Graywater discharges are not currently regulated in the U.S. (except for the Great Lakes), but national restrictions are anticipated for U.S. coastal waters and perhaps internationally.

Many ships are equipped with a Marine Sanitation Device (MSD) to collect and hold sewage during transit of the 3 nm no-discharge zone and when near to shore in other countries. Sewage holding times vary from ship to ship, but generally amount to about 12 hours. Current practice on many ships is to avoid the overboard discharge of graywater in port. Costly modifications to some ships are being implemented to increase wastewater holding times up to as much as 36 hours. Offloading wastewater while in port is expensive and costs are increasing worldwide.

An alternative to shipboard holding tanks is the use of wastewater treatment systems. Conventional land-based biological wastewater treatment plants rely on large aeration tanks with settling/clarification chambers and long (>20-hour) hydraulic retention time (HRT) to remove suspended solids and oxidize dissolved organic material. These systems require frequent attention, such as sludge wasting and periodic chemical additions (e.g. chlorine), and are space intensive. As a result, conventional biological systems are not particularly well suited for shipboard applications where space is a premium and manning is limited. Short-term aerobic biological pre-treatment, however, is an attractive concept when combined with membrane ultrafiltration systems. Membranes effectively reject a high percentage of suspended solids and bacteria, and the bio-conditioning would be expected to stimulate microbial activity that will consume the majority of the soluble organic content in the wastewater. If these systems can be designed to operate effectively at rather short residence times (<10 hours), they offer significant potential for shipboard non-oily wastewater treatment applications. This paper describes research and development efforts to demonstrate and validate the combined bio-conditioning and membrane-filtration concept, using both in-tank and external ultrafiltration membranes.

TECHNICAL CHALLENGES

Numerous conventional blackwater-graywater treatment processes have been evaluated for their ability to meet U.S. Coast Guard Marine Sanitation Device (MSD) effluent quality requirements, as well as shipboard operating requirements. However, most of these processes were determined not to be capable of meeting Type II MSD effluent quality requirements (fecal coliform limit of 200 cfu per 100 mL and total suspended solids limit of 150 mg/L) or were not suitable for shipboard use. Of particular concern for the shipboard application of conventional treatment systems are the: severely limited space available for installation, operation, and maintenance; low manpower available for operation and maintenance; and safety issues related to the storage and use of caustic, corrosive, and flammable chemicals required by the treatment processes.

Blackwater and graywater are high-strength waste streams (700-2500 mg/L biochemical oxygen demand and 300-1300 mg/L total suspended solids) composed of organic and inorganic particles and dissolved organic matter (starches, proteins, carbohydrates). Conventional filtration processes (media bed, strainers) are capable of removing the suspended matter to MSD Type II levels, but require frequent backwashing or filter media replacement. In addition, the large majority of methods capable of removing fecal coliform bacteria rely on biologically toxic chemicals that result in safety concerns for both the sailor and the aquatic organisms found in the receiving-water body.

The combination of performance goals (throughput and high-quality effluent) and the many constraints imposed by the shipboard environment result in a challenging engineering problem with a large number of technical and life-cycle cost trade-offs that must be analyzed. Some of the design constraints of the shipboard environment include: confined space available to install, operate, and maintain treatment systems; short deck-to-deck height; high-strength waste; widely variable waste in-flow rates; extended periods of no flow; high degree of automation required due to limited or no manning available for operation and maintenance; shock, vibration, and electromagnetic interference requirements; and safety issues related to the storage and use of hazardous chemicals.

One example of a trade-off that must be considered for a non-oily wastewater treatment system involves the limited space available to collect, hold, and treat the waste. On one extreme, a system could collect and treat the wastewater continuously over a 24-hr period, and on the other extreme the system could provide minimal holding capacity and treat the waste as it is generated, up to the peak flow rate. The former case results in the smallest treatment system and the largest holding tank; the latter case is the opposite scenario. Therefore, to determine the optimum combination of collection and holding tank size versus treatment system size and complexity, the design engineer must analyze a number of variables concurrently. The analysis for this example would consider the impact on treatment system performance (throughput and effluent quality) as well as the life-cycle cost of: continuous versus intermittent operation; ability of the chosen treatment process to manage rapid changes in waste characteristics as a result of minimal hold-up volume and mixing; and the time required to repair equipment versus the tank volume available to collect waste while conducting repairs.

The first step in solving the problem was a worldwide survey of industry for technologies suitable for the treatment of shipboard graywater and blackwater. The technologies were evaluated, in part, based upon their relative performance in key areas including: ability to meet anticipated effluent limits; modularity; level of process complexity; volume/area requirements; ability of the process to respond to changing conditions or upsets; and availability of performance documentation to illustrate process maturity. Two technologies were identified as appropriate for subsequent laboratory evaluations and development: membrane filtration and evaporation. The evaporative process was subsequently evaluated in the laboratory with graywater. Results showed that the system could not reliably meet effluent quality standards and, in addition, was far too large for shipboard use. More-promising results were obtained with membrane ultrafiltration and membrane filtration combined with aerobic conditioning of the waste.

MEMBRANE TECHNOLOGY

Membranes are thin barriers or films of material that allow certain substances to pass while rejecting others. Membranes that allow only some substances to pass through them are called semi-permeable membranes. Most commercially available membranes are made from polymers, ceramics, metals, or porous materials impregnated with liquid or gelatin-like substances. The pore size and distribution of the membrane material is designed to allow certain sizes of molecules, ions, and particles to pass and they are classified accordingly. Membrane throughput (flux) is controlled by the driving force (positive or negative pressure) and is reduced by the fouling rate. As with conventional filtration systems, membranes typically operate at room temperature.

Membranes provide a straightforward and relatively simple means to separate and concentrate waste streams (up to 98%), and thereby decrease waste volumes and provide the opportunity to substantially increase holding times. In addition, membrane systems require less space and power than phase-change processes such as vaporization, are relatively inexpensive, and have many components in common with other shipboard mechanical systems. In 1977, researchers found that ultrafiltration was an effective process for treating raw blackwater and activated sludge wastes, and for producing an effluent that met national discharge standards for total suspended solids and fecal coliform. These evaluations reported, however, that the membrane materials evaluated (mostly cellulosic) were not hardy and suffered rips and leaks. They also were not rigorous enough to withstand harsh cleaning procedures required to restore their performance. New membrane materials and manufacturing techniques, however, have been developed during the subsequent 15 years, which justified re-examination of membrane technology.

MEMBRANE – BIOREACTOR CONCEPT

The combination of membranes with biological wastewater treatment was first reported in 1969. The separation of activated sludge and effluent was accomplished with an ultrafiltration membrane and the biomass was recycled to the aeration tank. Many of the initial limitations of membrane separation have been overcome, making the membrane bioreactor (MBR) process a viable alternative to many conventional processes in biological wastewater treatment systems. The MBR process is similar in several aspects to a conventional activated sludge system, but instead of conventional final clarifiers, the MBR process employs membrane filtration to accomplish solid/liquid separation. The MBR process maintains higher biomass concentrations and uses smaller aeration tanks than conventional systems, while achieving comparable treatment. Membranes in the microfiltration and ultrafiltration range prevent the loss of biological solids and high-molecular-weight solutes from the bioreactor. The near-complete conversion of influent organic matter to carbon dioxide and water is accomplished by maintaining a high biomass concentration and the retention of high-molecular-weight compounds by the membranes. Since the membranes are able to retain the biomass, the solids retention time (SRT) is independent of the hydraulic retention time.

The MBR process is particularly suitable for situations where long solids retention times are necessary to achieve the removal of pollutants. Microbes (biomass) in the bioreactor require energy for biosynthesis and cell growth and a minimum amount of energy to maintain cell structure and integrity. The high biomass concentration in an MBR results in a high minimum maintenance energy in addition to the energy for cell growth. As a result of the high biomass concentration, a high oxygen demand must be satisfied in aerobic MBR systems to ensure continuous biosynthesis and cell growth. Maintaining a low ratio of food (influent waste) to micro-organisms in the reactor results in minimum sludge generation (and wastage), reduced plant size, and the development and retention of waste specific microorganisms. As shown in Figure 1, there are two basic MBR configurations. In the first configuration, membrane filtration follows an activated sludge reactor in a separate stage. This configuration is similar to membrane installations used in water treatment, and is referred to as "membrane separation activated sludge." A second configuration that has been introduced more recently places the membranes within the activated sludge reactor. This second configuration is often called "direct solid/liquid separation," "submerged membrane bioreactor," or an "immersed membrane bioreactor." Much work with these systems has been performed in Japan, where industrial wastewater, domestic wastewater, and septage are treated. Use of this process has been increasing gradually in North America. The technology may have potential as a retrofit to existing land-based facilities to improve treatment performance or increase capacity, as well as in the design of new plants. It may be most suitable in locations with limited space and/or operations staff. It is the last two features that make the MBR attractive to the operators of marine vessels.

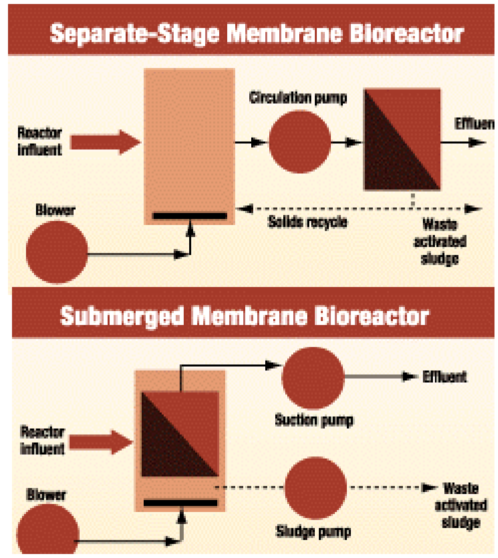

Figure 1. The MBR Process Has Two Basic Configurations

Membrane Technology Used in MBR Processes

Two of the most common membrane module arrangements employed for wastewater applications are tubular and hollow-fiber membranes. A tubular membrane essentially is a membrane installed inside a porous tube. Typically, pressurized feedwater enters the inside of the tube and exits perpendicularly through the membrane. A disadvantage of tubular membranes is their low surface-area-to-volume ratio, but they are superb for high-solids-bearing wastewater because of their resistance to plugging. When used in conjunction with a biological reactor, the tubular membrane module would be downstream of the biological reactor (i.e., a separate-stage system). Circulation pumps would generate the pressure required to drive the filtration operation. A hollow-fiber membrane is a compact bundle of flexible fibers. Generally, pressurized flow passes into the hollow fibers from the outside and the permeate moves out through the ends of the fibers. Hollow-fiber membranes have higher surface-area-to-volume ratios than tubular membranes and provide good resistance to clogging. In addition, the flexible membranes are capable of being "back-pulsed," or backwashed, without membrane damage. The hollow-fiber membrane is the type most commonly used in submerged MBR processes.

A third membrane configuration used in the MBR process is the flat-plate membrane panel housed within a rectangular box. Together with an integral coarse-bubble aeration system, the box is placed in the bioreactor. The membrane panels are oriented vertically and slotted into the top section of the box, allowing a small gap between the panels to minimize clogging. During operation, the aerated sludge rises up between the panels and causes the recirculation of sludge within the tank. Each membrane is connected to a permeate collection header, and the membrane effluent is drawn out by suction (vacuum) created by the available hydraulic head or by pump. The flat-panel membrane has a greater surface-area-to-volume ratio than tubular membranes, but less than hollow-fiber membranes.

Benefits of the MBR Process

The MBR will have a smaller footprint than conventional processes and since the process is operated at high mixed liquor suspended solids (MLSS) concentrations, there will be lower organic matter concentrations in the effluent. As a result, a smaller reactor will produce the same quality effluent for a given level of treatment. A smaller reactor and the absence of final settlers result in a relatively compact system. Since membranes, instead of settling tanks, clarify the reactor effluent, MBR processes are able to operate at long sludge ages without degradation of effluent quality. The operating sludge age of a conventional system often is limited by the sludge's settling performance in the final clarifiers. In contrast to conventional activated sludge systems, changes in the microbial population, such as the development of pin floc or filamentous floc, have virtually no impact on the effluent quality of MBR processes. As a result, the necessary sludge wasting and the solids handling operations can be performed after relatively long intervals as a batch operation. Some researchers have reported sludge wasting to be virtually eliminated.

What may be the greatest attribute of the MBR process is the ability of these systems to function well with little operator attention, and usually with little knowledge of the microbiological aspects of the process. In conventional treatment, bulking sludge and other changes in the activated sludge microbial populations can diminish the overall effluent quality. In order to avoid possible degradation in effluent quality, the conventional treatment processes require constant supervision by qualified personnel. In the MBR process, because the solids separation step is virtually independent of the microbial population, the supervision and expertise required are significantly reduced. The lack of required operator attention is an important benefit to agencies and communities where personnel would not be available for frequent monitoring and adjustment. Also, only intermittent wasting of solids and the relatively small volumes of material generated further reduce the operator attention required.

MBR Disadvantages

The primary disadvantage associated with MBR is membrane fouling or clogging, which will be different for each application. As a result, the membranes' operating life has not been firmly established yet. Fouling results from the accumulation and attachment of particulate and dissolved material at the surface of the membrane, which causes a significant resistance to filtration. In addition, the presence of stringy material, such as hair or textile fibers, will significantly reduce membrane operation. This could be a major consideration for applications without fine screens or a high degree of primary treatment. Both MBR configurations will periodically require some form of chemical membrane cleaning. This can be accomplished with a chlorine solution or sometimes by immersion in an acid bath. However, the additional chemical storage and handling requirements created may be undesirable at some facilities, although membrane cleaning would not necessarily have to be performed aboard ship. The circulation pumps used in the separate-stage MBR can consume considerable energy. This can lead to relatively high operating costs and may limit its applications. In contrast, the submerged configuration does not require a circulation pump and can, therefore, operate with significantly less energy.

Operating Parameters

Table 1 presents some key operating parameters for MBR systems reported in the literature. Both separate-stage and submerged MBR systems are presented because there appear to be few differences between their operating parameters and capabilities. Many systems reported excellent chemical oxygen demand (COD) removal, with removal percentages exceeding 90 percent. Although the table covers a wide range of parameters, one general observation can be made. The systems treating influent wastes greater than 1000 mg/L COD operated with HRTs greater than two hours and at MLSS concentrations of more than 10,000 mg/L. Some of the systems treating wastes comparable to domestic sewage (400 mg/L COD) were operated at HRTs of less than two hours.

Design Considerations

The most important design factor for an MBR system is the membrane flux, a measure of the volume of fluid processed per unit of membrane surface area (analogous to a loading rate). The operating flux and the plant flowrate will establish the number of modules required. The lower the operating flux, the greater the number of modules required. For MBR processes, the aeration system capacity and design require careful consideration. One researcher reported that the aeration requirements to maintain the necessary turbulence over the membranes are even greater than the requirements for biological treatment when operating at high mixed liquor concentrations. Furthermore, when operating at long sludge ages, the system may nitrify, converting ammonia to nitrate and consuming additional oxygen. To retrofit an existing system, significant changes may be required, depending on the tank configuration, the types of blowers, and the number of diffusers. For an activated sludge aeration tank, air typically is introduced though submerged diffusers. The lowest-maintenance diffusers that could be used would be coarse-bubble, non-clog diffusers. These generally provide poor oxygen transfer efficiency (OTE); that is, they do not effectively transfer oxygen from the air into the wastewater. The depth of submergence also affects the OTE of diffusers. Therefore, the selection of diffuser technology and the tank depth will affect the number of diffusers required. Another factor to consider in a potential application is the clearance available above and around the reactor. Although both MBR configurations have small footprints, submerged systems require module removal from the tank's top. Therefore, a significant amount of clearance is required, which may be a constraint in the shipboard environment.

US NAVY SYSTEM DEVELOPMENT AND DEMONSTRATIONS

Aerated Membrane Treatment System

Based on successful bench-scale testing, a shipboard scale (75-person) Aerated Membrane Treatment System (AMTS), with submerged in-tank hollow-fiber membrane modules, was designed, fabricated, and demonstrated pierside. The transportable prototype AMTS processes 2.5 gal/min of non-

Table 1. MBR Operating Characteristics Reported in Literature (Heiner and Bonner)

Source	Configuration	Flow (gal/day)	Intit COD (mg/L)	HRT (hours)	SRT*** (days)	MLSS (mg/L)	COD Removal %	Pore size (µm)	Flux (gal/ft^2-day)	Appl press (kPa)	Appl press (psi)
Benitez	Submerged	5.5	>1000	10.5	-	25,000	63-88	0.1	-	20	2.9
Shimizu	Submerged	238	200*	12	-	3000	-	0.1, 0.5	10	30	4.4
Zhang (a)	Separate	105,650	80-130	0.5	16.8	4700	-	-	-	-	-
Zhang (b-1)	Submerged	16	300	1	-	2500	-	-	-	-	-
Zhang (b-2)	Separate	105,650	350*	0.5	16.8	8000	-	-	-	-	-
Zhang (b-3)	Separate	13,206	2320	2.8	8.2	14,500	-	-	-	-	-
Zhang (b-4)	Separate	13,206	4000	4.5	9.7	15,000	-	-	-	-	-
Pound	Submerged	4465	356	2	-	5000-15,000	95	0.2	20	30	4.4
Yamamoto	Submerged	1.9	250	4	-	14,000-16,000	90-93	0.1	0.6	13	1.89
Yamamoto	Submerged	0.4	1000	20	-	14,000	92	0.1	0.12	40-60	5.8-8.7
Yamamoto	Submerged	0.4	4660	20	-	36,000	99	0.1		-	-
Yamamoto	Submerged	0.4	9900	20	-	47,000	63	0.1	0.09	70	10.2
Cicek	Separate	42.3	325	6	30	12,200	99	0.2**	49	30-40	4.4-5.8

*Reported BOD level only **Approximation only; molecular cutoff reported at 300 kilodaltons *** Solids retention time

oily wastewater generated from ships equipped with gravity-collected graywater and vacuum-collected blackwater systems. The system is intended to meet effluent the quality standards shown in Table 2 and to provide at least a 15-day holding capacity by concentrating the feed stream > 40:1. The transportable AMTS prototype fits in a 12m-long mobile trailer and consists of a pierside equalization/collection tank, a treatment tank consisting of a bioreactor section, a membrane filtration section (containing several submerged hollow-fiber modules), and a sludge retentate holding section. Isometric schematics of the system are shown in Figure 2 and Figure 3. Figure 4 is a photograph of the system being operated pierside.

Table 2. Effluent Quality Performance Goals for Graywater Treatment

Water Quality Parameter	Effluent Water Quality Goal
Biochemical Oxygen Demand (BOD_5)	≤ 50 mg/L
Total Suspended Solids (TSS)	≤ 100 mg/L
Fecal Coliform (FC)	≤ 200 colony forming units / 100 mL

The purpose of the demonstration was to evaluate the performance of an automated system using actual ship-generated wastewater. The AMTS was operated from May-October 1999. The demonstration was conducted in four phases: setup (May 5-7), startup (May 8-15), debugging (May 16-July 8), and processing (July 9-October 20). The system processed wastewater for a total of 1,805 hours at 2.3 gal/min. The membrane resistance trend indicated that the membranes could process approximately another 5,000 hours before any chemical cleaning would be needed. The effluent quality goal of 90% success with 95% confidence was met throughout the demonstration for TSS and fecal coliform. During the early part of the test, the system did not meet the goal for five-day BOD because of a limited oxygen transfer to the biomass. Modifications to the system corrected this problem. Overall, the demonstration showed that shipboard non-oily wastewater could be processed and that BOD_5, TSS, and fecal coliform could be significantly reduced.

Tubular Membrane Prototype

Concurrent with the AMTS demonstration, a prototype graywater treatment system based on the use of external (out-of-tank), large-bore (~25mm-diameter) bundled tubular membranes was designed. Each bundled module consists of 8 tubes that are 2m long, arranged in a heat-exchanger configuration. The macerated and aerated wastewater is biologically

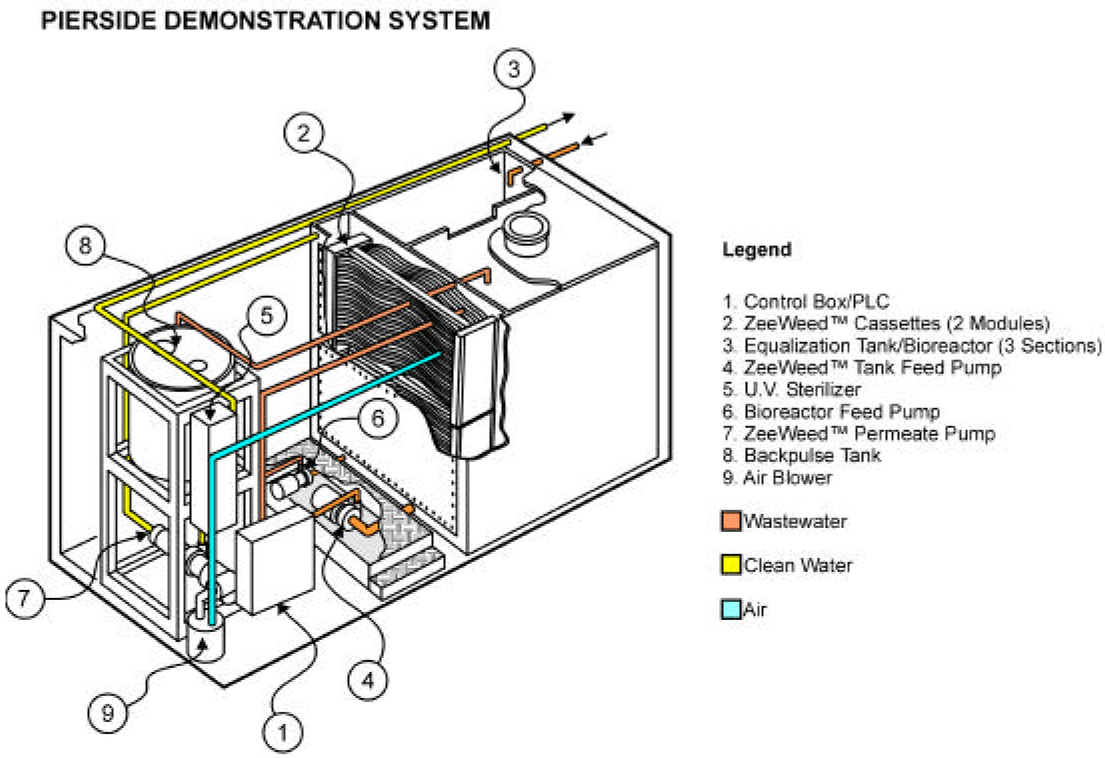

Figure 2. Isometric Flow Schematic of Large-Scale AMTS (In-Tank Membranes)

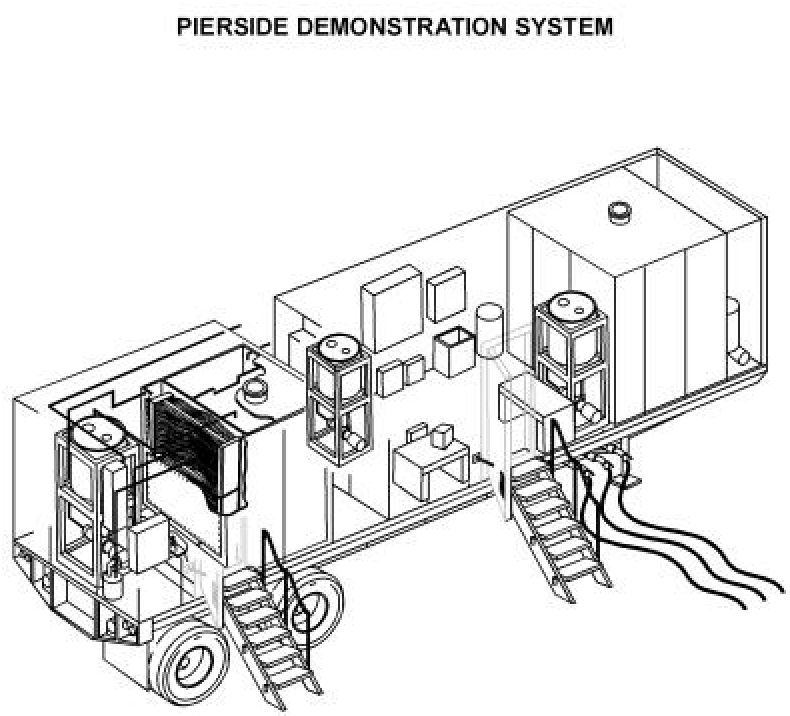

Figure 3: Isometric Schematic of Large-Scale AMTS (In-Tank Membrane System) Trailer

Figure 4. Prototype AMTS (In-Tank Membrane System) Undergoing Pierside Testing

conditioned at a retention time of 8 hours and recirculated through the ultrafiltration tubes. The “clean” water permeates through the walls of the membranes and the retentate is held in the aeration holding tank. The effluent is pumped through an ultraviolet (UV) light reactor to ensure that it is sterile prior to discharge. The prototype has a capacity of approximately 10 L/min and will concentrate the graywater at 50:1. Figure 5 is a photograph and Figure 6 is a schematic of the prototype system. Figure 7 shows the tubular membrane bundle and Figure 8 shows the UV light reactor.

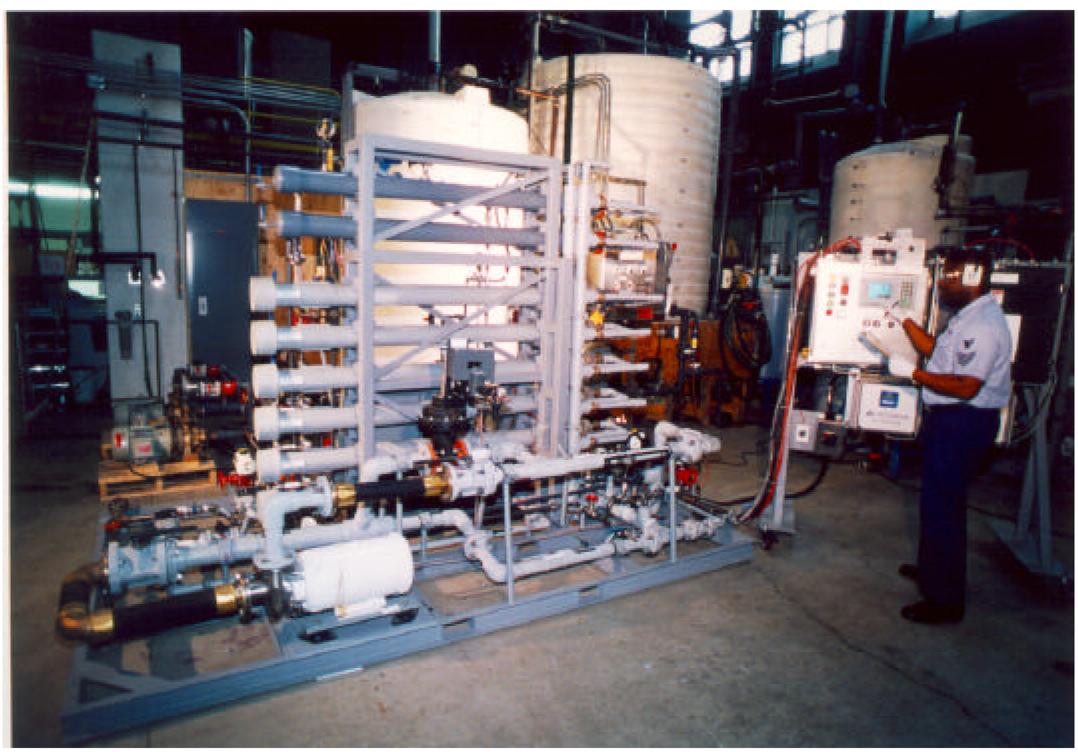

Figure 5. Tubular-Membrane Prototype System in the Laboratory

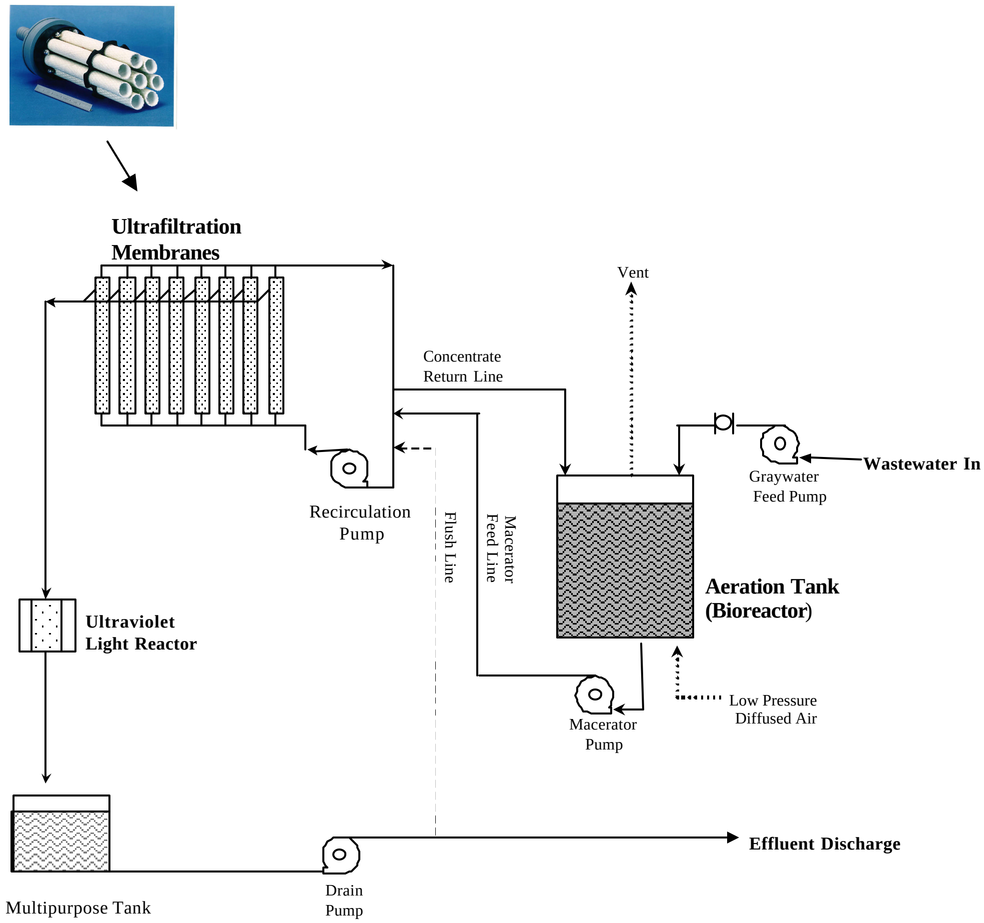

Figure 6. Simplified Schematic of Tubular-Membrane Prototype System

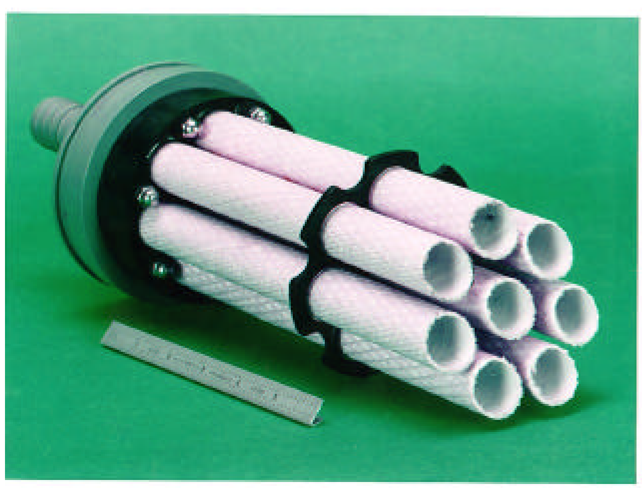

Figure 7. ZPF-8 Membrane Module used in Tubular-Membrane Prototype System

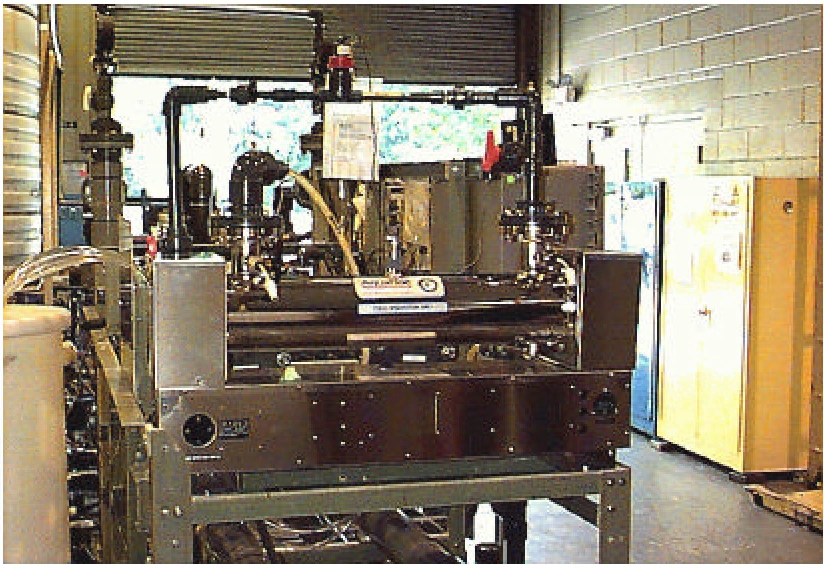

Figure 8. Aquafine Four-bulb Ultraviolet Light Reactor for Disinfection

A comprehensive and phased laboratory evaluation was conducted under realistic shipboard scenarios to characterize system performance relative to design goals for throughput, effluent quality, and reliability. During the laboratory evaluation, the tubular membrane prototype system was operated automatically (unmanned) for 24 hours/day, processing graywater for approximately 15 hours/day at 2.5 gal/min. Approximately 2,500 gallons of raw graywater was processed daily. While processing, aerated graywater was pulled from the aerated holding tank (bioreactor) and concentrated in the membrane loop as permeate was continuously removed. Raw graywater was supplied to the bioreactor in a ratio of 1 part galley to 10 parts laundry wastewater; this ratio resulted in a graywater mixture with characteristics similar to shipboard graywater. This raw graywater was added to the bioreactor in a schedule representative of a vessel's anticipated graywater generation rate (see Figure 9). Based on the graywater transfer and resulting treatment schedule, one tap-water flush of the treatment system was conducted each day at approximately 2300 hours (11:00 PM) with an average flush temperature of 50^{o}C. During phase 1 of the evaluation, the prototype was operated for 37 consecutive days (600 hours). This test simulated more than 30 days of operation in which the ship would be independent of shoreside support. The system met the test objectives for throughput (2.5 gal/min), effluent quality for TSS and fecal coliform, reliability (no equipment failures), and sludge retention (30 days). Although the system only met the BOD effluent quality goal for two-thirds of the samples, the average and geometric mean values for the entire sample set met the goal of 50 mg/L. The samples that did not meet the effluent quality goal may have resulted from inadequate bioreactor aeration at particular points throughout the test; acceptable BOD values were noted as early as the second test day, which indicates a rapid start-up of the bioreactor.

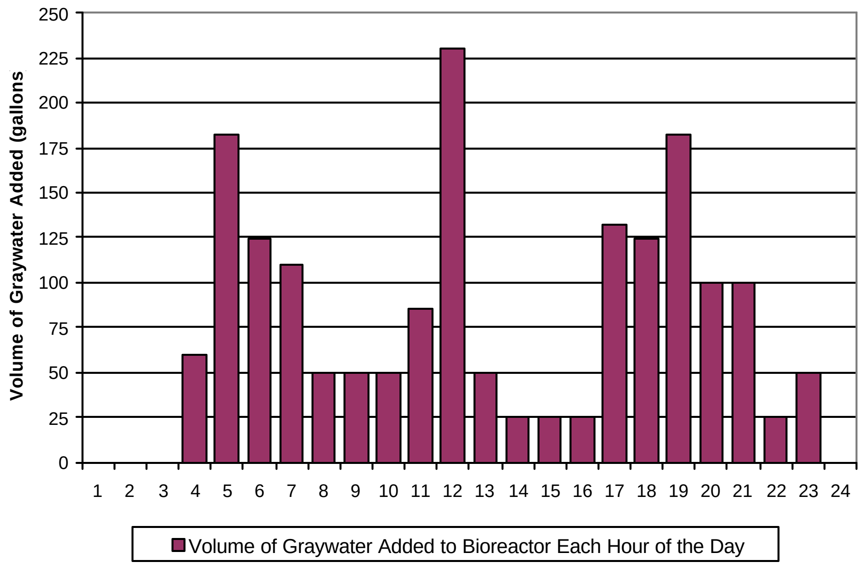

Figure 9: Typical Profile for Ship Graywater Generation

During phase 2 of the evaluation, the prototype was operated for 40 consecutive days (430 hours), during which graywater was processed for 30 days. The system processed graywater 15 hr/day during the 5-day workweek and remained idle (without graywater feed) over the weekends. This test simulated a series of consecutive ship transits separated by short periods in port. In this test, the treatment system must quickly alternate between no use and full use, a major challenge for biological treatment systems. The system succeeded in meeting all test objectives for throughput (2.5 gal/min), effluent quality, reliability, and sludge retention (30 days).

During phase 3 of the laboratory evaluation, it was determined that the membranes needed to be chemically cleaned to meet the six-month performance goal. The evaluations also identified a relationship between accelerated membrane fouling and insufficient graywater pretreatment and high membrane flux rate. In addition, the evaluations showed that the bioreactor became oxygen-transfer limited with time, which results in inconsistent effluent quality as measured by BOD_5. The system volume is, however, adequately sized to meet the treatment goals, but must be reconfigured to improve oxygen transfer, limit short-circuiting of raw waste ,and mitigate foaming. The laboratory evaluation demonstrated that 30-day sludge retention is achievable when processing graywater using the combined membrane bioreactor process. Effluent quality goals for total suspended solids and fecal coliform were met during each phase of the laboratory evaluation. However, improved aeration is needed to meet BOD_5 goals.

CONCLUSIONS

With a small footprint and little operator attention, membrane bioreactors are an appropriate technology for many marine wastewater treatment applications. However, several important factors should be considered when evaluating these systems. These factors include:

- Operating pressures and fluxes, which will establish the number of modules required.
- Pretreatment and screening needs and maintenance protocols, which will establish the manpower required.
- Aeration requirements and aeration capacity available.
- Energy consumption and annual maintenance costs.

The two MBR treatment systems described each have their own set of advantages and disadvantages with regard to potential shipboard wastewater treatment applications. The in-tank hollow-fiber membrane design has potential savings in space, weight, energy, and operational cost. The out-of-tank tubular membrane design provides for easy access and maintenance of the membranes without the need to drain and gas-free a wastewater tank. The large-channel tubular membranes are also well suited to wastewater streams that contain high solids concentrations and fibrous material.

In conclusion, these prototype systems were designed to meet unique shipboard challenges and requirements. Both systems were evaluated in the laboratory using land-based graywater mixtures and the in-tank membrane system was also tested pierside using ship-generated wastewater. They both use polymeric membranes to trap coarse and fine solids and to remove significant amounts of BOD and fecal coliform bacteria. Aerobic conditioning of the wastewater in conjunction with membrane filtration has been evaluated to ensure that anticipated BOD effluent quality goals can be met. Both systems use an enclosed ultraviolet light reactor to ensure disinfection of the UF membrane effluent.

DESCRIPTION OF SYSTEM OPERATION PARAMETERS

Flow rate = the volume of graywater processed over time. Assuming that a ship generates on average 30 gallons of graywater per person per day, and that graywater is being generated for 17 hr/day, a graywater treatment system serving 75 people must process 2.5 gal/min of graywater. If the graywater treatment system cannot maintain this rate, the system will overflow.

Permeability = the flow rate normalized to a common temperature and pressure (20^oC, 1 bar). The permeability shows the relative ease with which permeate passes through the membranes (while the system maintains a constant programmed permeate flow rate). A slow decrease in permeability over time is usually indicative of membrane fouling (either particulate or biological), which can build up on the surface and/or in the pores. A sudden decrease in membrane permeability may indicate a blockage.

TMP = “Transmembrane Pressure,” as determined by the average pressure across the membrane surface (tube to shell). (In some tests, TMP is referred to as THP (transheader pressure) because the pressure transducers were mounted on the membrane headers rather than on the membranes themselves.) Not only does the TMP demonstrate the pressure drop through the membranes, but is also provides a safety parameter for the fairly fragile membranes. The polymer membranes used should not have a TMP higher than 45 psi (based upon an assumed maximum safety inlet pressure of 65 psi and the system’s piping configuration), as a higher pressure can cause rupture.

Description of Treatment Parameters

BOD = “Biological Oxygen Demand.” The BOD is a measure of how much organic matter is available as food in the graywater. A low BOD (<50 mg/L) is desirable in overboard effluent, since algae blooms and other prokaryote outbreaks occur when high nutrient levels are available. In most wastewater testing, the BOD is analyzed over a five-day period and is reported as BOD_5. A bioreactor is critical in reducing BOD as the bacterial population digests the organics initially present in the graywater.

TSS = “Total Suspended Solids.” The TSS is a measure of the amount of suspended solids, both organic and inorganic, found in the wastewater. A TSS level below 100 mg/L is desirable in overboard effluent.

FC = “Fecal Coliform.” Fecal Coliform (FC) is a common bacterium found in wastewater that can cause gastric disease in humans. Levels of fecal coliform are measured in “colony forming units” (cfu, essentially a bacterium capable of reproducing), per milliliter of wastewater. Overboard effluent should have less than 200 cfu/ml.

Oils and Greases (O/G) = the amount of oils and greases found in graywater. There are no regulatory limits on the amount of oils and greases present in the effluent, but it has been surmised in the laboratory that high O/G levels in the bioreactor prevent the bacteria from effectively reducing BOD.

Definitions

Concentrate: The portion of the feed solution that does not pass through the membrane, but is retained within the processing loop (retentate).
Daily Clean Water Flush: The systems are flushed at the end of each test day with 50°C tap water to clean all concentrate off the surface of the membranes.
Hydraulic Retention Time: The average amount of time a theoretical graywater molecule is retained in the system before exiting (overboard) as effluent.
Membrane Flux: Liters of permeate produced per square meter of membrane per hour, normalized to 20°C.
Operational Run Time: The cumulative time the system is powered and available to process graywater (clock time).
Permeability: Liters of permeate produced per square meter of membrane per hour, normalized to specific temperature and pressure (20°C, 1 bar). This parameter, designated Q_{20}, is an indicator of membrane fouling.
Permeate: The portion of the feed solution that passes through the membrane.
Processing Time: The time the system is actually processing graywater.
Transheader Pressure: Transmembrane pressure as measured off the membrane headers versus the membranes themselves.
Transmembrane Pressure: The effective pressure at the membrane surface as calculated by:

$$\left(\begin{matrix}\text{Trans. Mem.}\\ \text{Pressure}\end{matrix}\right) = \frac{\text{Inlet Pressure} + \text{Outlet Pressure}}{2} - \left(\begin{matrix}\text{Permeate}\\ \text{Pressure}\end{matrix}\right)$$

Volume Reduction: 20:1 volume reduction means that of 20 gallons of feed water processed, one gallon of concentrate remains.

Abbreviations

‘	Feet
“	Inches
°	Degrees
Ave	Average
BOD_5	Five-day biochemical oxygen demand
cfm	cubic feet per minute
cfu	Colony-forming units
FC	Fecal coliform
ft^2	Square feet
ft/s	Feet per second
gal/min	Gallon per minute
GW	Graywater
Hp	Horsepower
HRT	Hydraulic retention time
LMH	Liters per square meter per hour
mg/L	Milligrams per liter
MPN	“Most Probable Number”: an analytical method for counting bacterial colonies
MWCO	Molecular weight cut-off
n/a	Not applicable
Perm	Permeate
PVC	Polyvinyl chloride
psi	Pounds per square inch
PTFE	Polytetrafluoroethylene
Q_{20}	Permeability [normalized to 1 bar and 20°C]
Temp	Temperature
THP	Transheader Pressure
TMP	Transmembrane Pressure
TSS	Total suspended solids
UF	Ultrafiltration
UV	Ultraviolet
VAC	Volts alternating current

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